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AN INDUCTIVELY COUPLED FILTER PROVIDING COMPLETE RF SHIELDING OF AN ELECTROEXPLOSIVE DEVICE

TECHNICAL DOCUMENTARY REPORT NUMBER RTD TDR 63-3005

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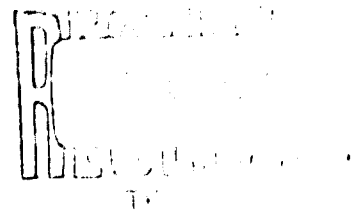
Research and Technology Division
Air Force Systems Command
AIR FORCE WEAPONS LABORATORY
Kirtland Air Force Base
New Mexico

Project Number 5791, Task Number 579111

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1 July 1963

E R R A T U M

RTD TDR 63-3005.   AN INDUCTIVELY COUPLED FILTER PROVIDING COMPLETE
RF SHIELDING OF AN ELECTROEXPLOSIVE DEVICE

FOREWORD: Last line of paragraph 2 should read as follows:

    "RF energy into a shield is an inverse function of the square
root of the frequency."

FOREWORD

This report is a technical paper presented at the HERO Congress at the Franklin Institute during 30 April to 2 May by the Bjorksten Research Laboratories of Madison, Wisconsin. Bjorksten Research Laboratories are performing the work described under contract AF 29(601)-5358 for the Air Force Weapons Laboratory.

Project 5791, Task 579111, was established to develop a technique to protect electroexplosive devices from inadvertent firing by RF energy induced in their leads. Under this task, Bjorksten has developed a shielded pulse transformer with the secondary and bridge wire completely shielded from RF energy by a metal case with the primary wound around the outside. The protective principle is based on the fact that the depth of penetration of RF energy into a shield is an inverse function of the square of the frequency.

This report is preliminary and very briefly describes the success of the technique to date. To the knowledge of the Air Force Weapons Laboratory, this is the first application of the skin effect theory to filtering RF energy from squibs. A detailed engineering report will be published in August 1963 upon completion of the current contract.

ABSTRACT

A filter is described which will protect an electroexplosive device from RF hazards by completely enclosing the electroexplosive device within a metallic shield that has no openings or leads passing through. Intentional firing is accomplished by inductive coupling through the shield. Experimental power attenuation vs. frequency curves and the delivered intentional firing energy of a filter of practical size and weight are presented.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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CONTENTS

v

ILLUSTRATIONS

1. INTRODUCTION

The use of an electroexplosive device (EED) in an RF environment presents two simultaneous requirements--RF protection must be provided and intentional firing capability must be preserved.

As far as the RF problem is concerned, a simple and foolproof solution is to enclose the EED within a continuous shield of adequate thickness that has no openings whatsoever for the entry of RF energy. Because of the inverse relationship between skin depth and frequency, such a shield provides unquestioned protection against all frequencies above some lower limit.

As far as the intentional firing problem is concerned, a simple solution that is compatible with the presence of a continuous shield around the EED is the use of low-frequency inductive coupling. Because of the relative penetrability of the shield at low frequencies, enough energy can be transferred to ensure reliable firing of the EED within the shield. Figure 1 illustrates this general approach.

The cross-hatched member represents the continuous metallic shield which completely encloses the EED. It is clear that RF energy can not reach the EED without first penetrating this shield.

For intentional firing, closure of the switch in figure 1 allows current from a battery, a low-frequency generator, or a discharging condenser to flow in the outer coil. If this current in the outer coil is produced by a battery, it will establish a final steady-state flux that links the inner coil. Since a time rate of change of flux will occur in the inner coil as the flux changes from its initial to its final value, an activating pulse of current will flow through the EED. Similarly, if the current in the outer coil is produced by a generator of a low frequency such as 60 cps, 400 cps, or even 1,000 cps, an alternating flux will penetrate the shield, link the inner coil and cause an activating current to flow through the EED. Finally, if the current in the outer coil is produced by a discharging condenser, the flux associated with this transient will also penetrate the shield, link the inner coil, and cause an activating current to flow through the EED.
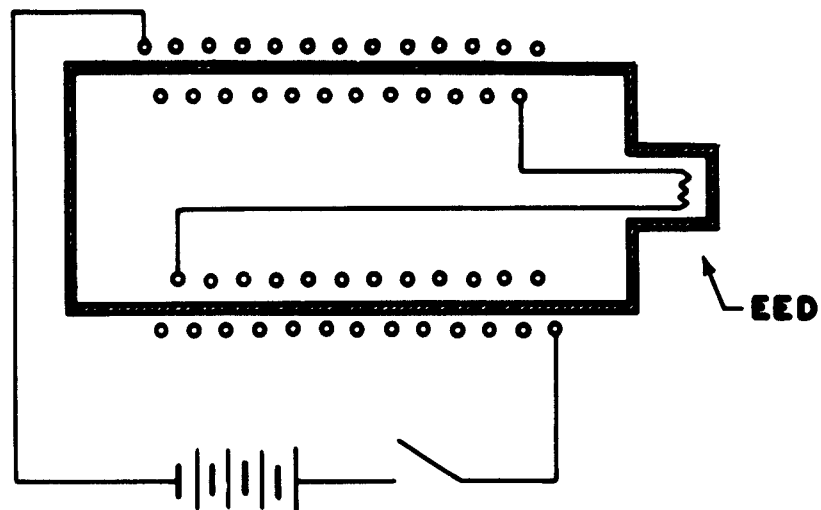
1

Figure 1. A schematic illustration of a completely shielded,
inductively coupled filter.

Positive protection from RF is achieved by totally
enclosing the squib circuit within a shield of
adequate thickness. Intentional firing is accomplished
by low-frequency inductive coupling.

Of course, energy transfer to the EED is improved by the use of magnetic materials. Figure 2 illustrates one geometry where the flux through the inner coil closes through a continuous path of magnetic material. It is seen that this geometry does not destroy the integrity of the shield; the only difference between the shields of figures 1 and 2 is that a magnetic material explicitly forms at least a part of the shield in figure 2.

These completely shielded, inductively coupled filters have been under development by the Bjorksten Research Laboratories since early 1961 when this approach was conceived by us. Work on these filters has been supported by the Air Force Special Weapons Center for the past year under Contract No. AF 29(601)-5358. Data obtained on this Air Force program constitute the major part of this paper.

2. A FILTER FOR THE MK-1 SQUIB

a. Intentional firing.

Figure 3 is a photograph of a filter designed for the MK-1 squib and a 28-volt dc firing system. This filter weighs 1.6 ounces, is 1.4 inches long, has a diameter of 0.67 inch, and a dc input resistance of 8.9 ohms. The 8.9-ohm input resistance ensures that the current drawn from a 28-volt supply does not exceed 3.15 amperes. While a squib is shown as being directly joined to the filter, it could be located a distance from the filter if the integrity of the shielding were preserved by some suitable means such as copper, or perhaps soft iron tubing.

Figure 4 shows a 28-volt step-wave input to the filter of figure 3 together with the corresponding output voltage pulses that are obtained when the load is either a 1-ohm resistor or a MK-1 squib. The voltage pulses for these two loads are easily identified because of the discontinuity associated with the firing of the squib. In this instance the squib has fired 0.2 millisecond after application of the input voltage. Taking 1.7 millijoules as the maximum energy required to fire a MK-1 squib under these conditions, and noting that the total energy delivered to the 1-ohm resistor is 13.9 millijoules, the safety factor for firing the squib is found to be at least 8.
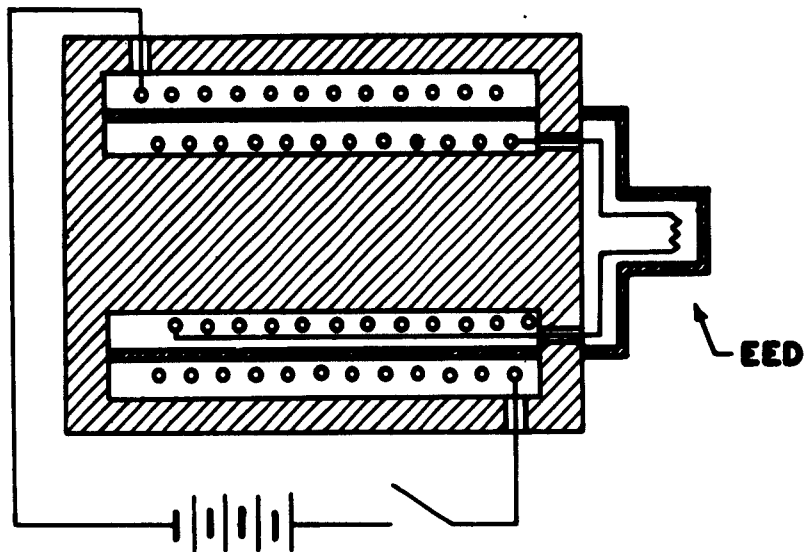
Figure 2.   A schematic illustration of a filter having flux closure
            through a magnetic material.

            This illustrates one way of obtaining flux closure through
            a continuous path of magnetic material without destroying
            the integrity of the continuous RF shield.

4
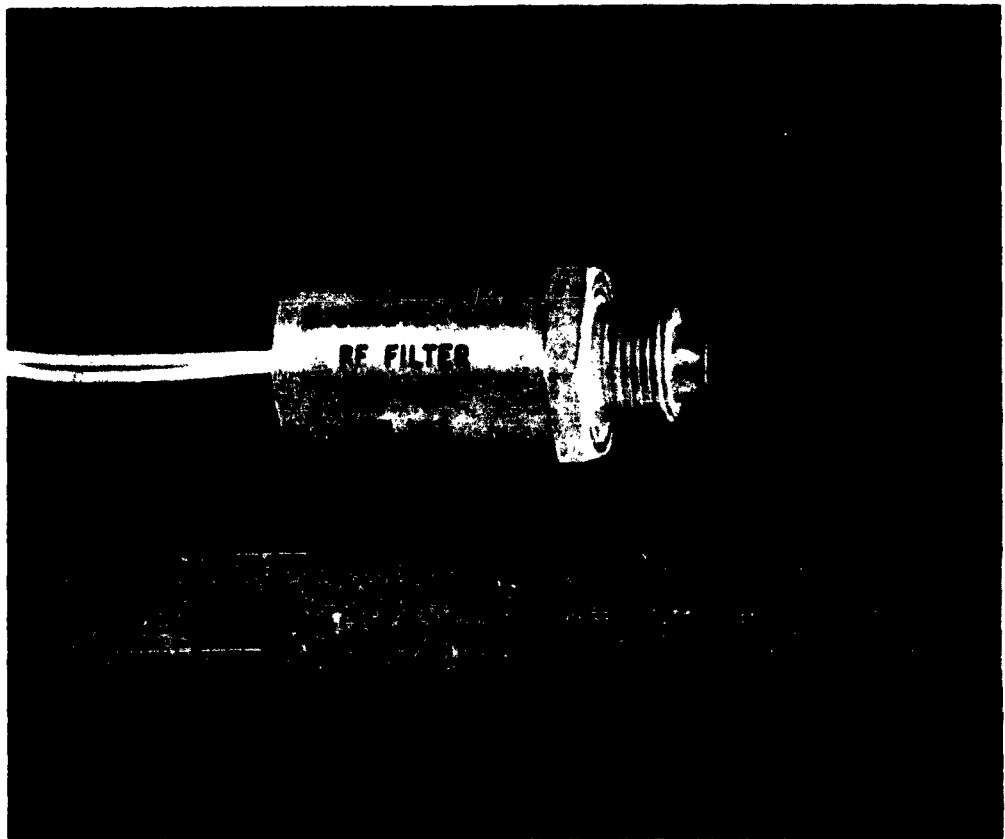
Figure 3.   A photograph of a filter designed for the MK-1 squib.

This filter delivers 13.9 millijoules to a 1-ohm load
upon application of a 28-volt step-wave input. This
is more than 8 times the energy needed to fire a
MK-1 squib which is shown at the right-hand end of
the filter. The power attenuation of this filter when
terminated by a 1-ohm load is 32 db at 200 kc.

5

Figure 4. A graph of output voltages for a 28-volt step-wave input.

Curve B shows the output voltage across a 1-ohm load for the filter of figure 3 when a 28-volt step wave (curve A) is applied to its input. Curve C shows the corresponding output voltage across a MK-1 squib load. In this instance the squib has fired 0.2 millisecond after application of voltage to the input of the filter.

6

There is also more than an adequate amount of energy delivered to a squib by the filter of figure 3 if the input voltage is as low as 20 volts. This is illustrated by the curves of figure 5 that show a 20-volt step-wave input and the output voltage pulses that are obtained when the load is either a 1-ohm resistor or a MK-1 squib. In this case the squib has fired 0.33 millisecond after application of the input voltage and the total energy delivered to the 1-ohm resistor is 9.5 millijoules. The safety factor for firing the squib is therefore about 5.6.

While it is very unlikely that an input voltage would accidently have a time constant as long as 1 millisecond if it were intended to be a step wave, the filter of figure 3 would fire a MK-1 squib with such an input even it it rose to only 20 volts. This "worst case" is shown in figure 6. The input voltage to the filter rises exponentially to 20 volts with a time constant of 1 millisecond (i.e., it reaches 90 percent of its final value in about 2.3 milliseconds) and the MK-1 squib fires 1.37 milliseconds after the start of the input pulse. The total energy delivered to a 1-ohm load in this case is 7.0 millijoules, and the safety factor for firing the squib is therefore about 4.1.

Figure 7 shows the energy delivered to the load as a function of load resistance when the input to the filter is a 28-volt step wave. It is seen that this energy varies by only 10 percent over the range from 0.7 ohm to 1.3 ohms which is the range of bridge wire resistance for MK-1 squibs. Of course, if the filter had been designed for a squib of a different resistance, then this curve would be centered at that value of resistance.

Figure 8 illustrates the effect of contact bounce in the switch that applies the input voltage to the filter of figure 3. In this case the switch was specially selected to have a large amount of contact bounce. For reference, the "clean" curve shows the output voltage across a 1-ohm load when the input to the filter is a "clean" 28-volt step wave. The other curve shows the corresponding output voltage that results when the switch in the input circuit has a large amount of contact bounce. It is seen that this bounce only delays the output pulse; the energy content of the output pulse is essentially unaffected.
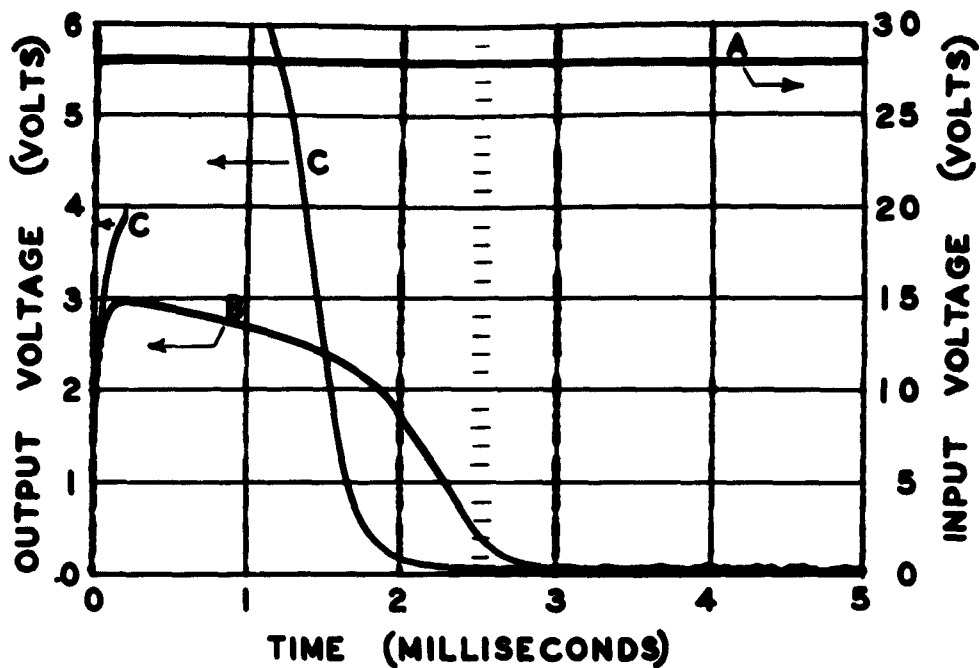
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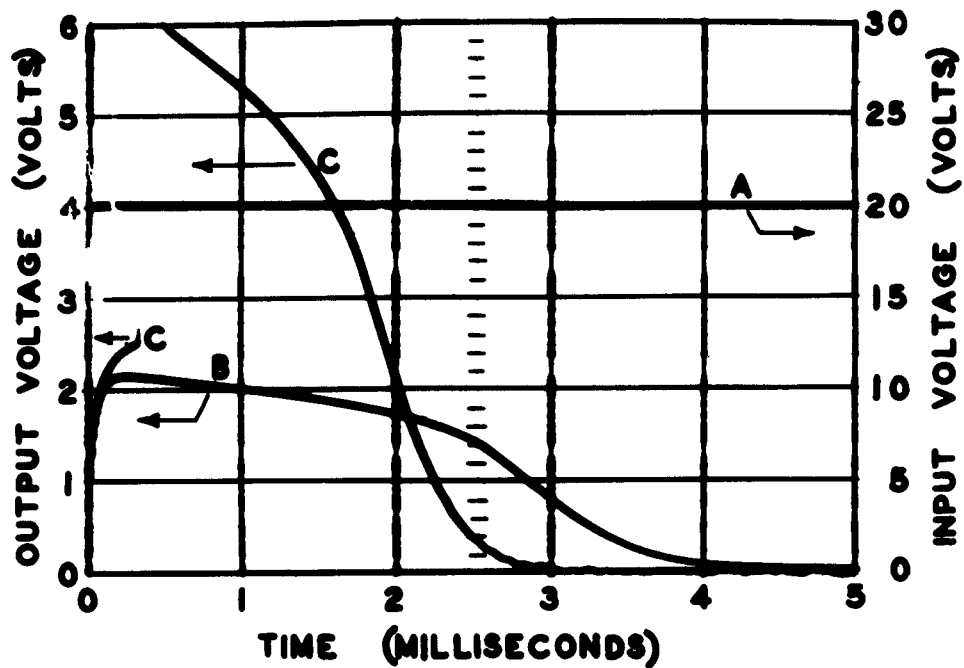
Figure 5.   A graph of output voltages for a 20-volt step-wave input.

Curve B shows the output voltage across a 1-ohm load
for the filter of figure 3 when a 20-volt step wave
(curve A) is applied to its input.   Curve C shows the
corresponding output voltage across a MK-1 squib
load.   In this instance the squib has fired 0.33 milli-
second after application of voltage to the input of the
filter.

8
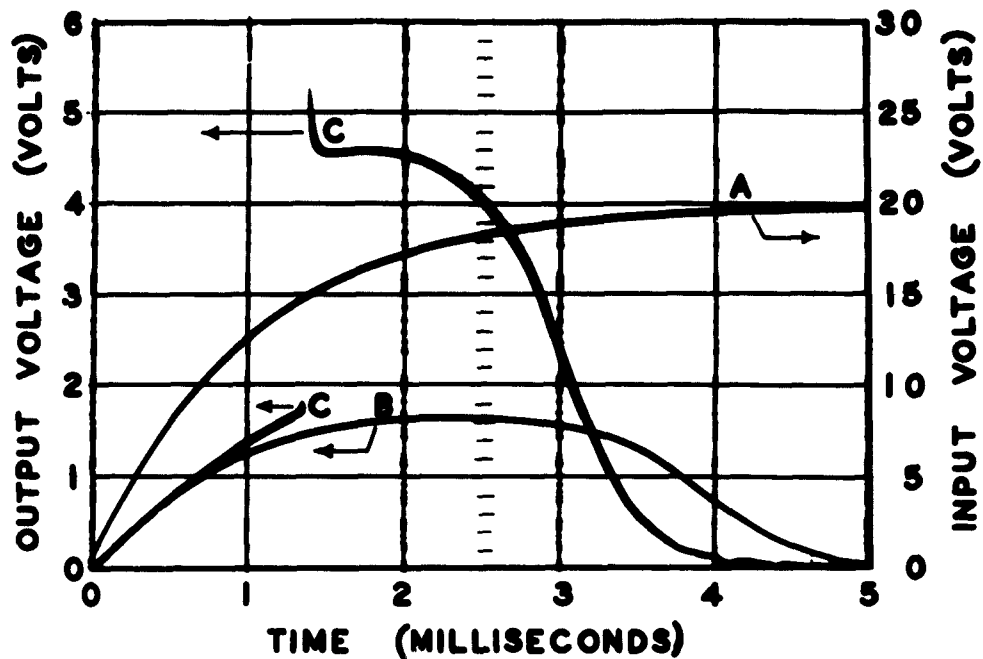
Figure 6. A graph of output voltages for an input voltage
rising exponentially to 20 volts with a time
constant of 1 millisecond.

Curve B shows the output voltage across a 1-ohm
load for the filter of figure 3 when the voltage
shown by curve A is applied to its input. Curve
C shows the corresponding output voltage across
a MK-1 squib load. In this instance the squib has
fired 1.37 milliseconds after the start of the input
voltage to the filter.

9
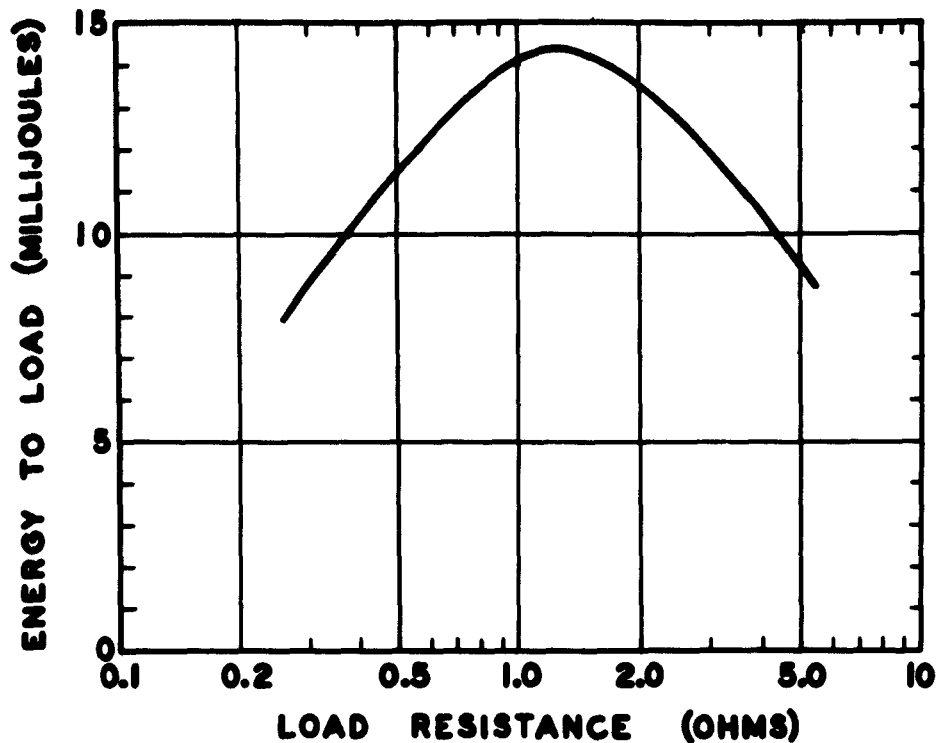
Figure 7. A graph of total energy delivered to the load vs. load resistance.

For a 28-volt step wave applied to the input of the filter of figure 3, this graph shows the total energy delivered to a load as a function of load resistance. This energy varies by only 10 percent over the range from 0.7 ohm to 1.3 ohms which is the range of bridge wire resistance for MK-1 squibs.

10

Figure 8. A graph showing the effect of contact bounce in
the input circuit of the filter of figure 3.

For reference, curve B shows the output voltage
across a 1-ohm load for the filter of figure 3 when
a "clean" 28-volt step wave (curve A) is applied to
its input. Curve C shows the output voltage across
a 1-ohm load when a switch specially selected to
have a large amount of contact bounce is used to
connect a 28-volt dc supply to the input of the filter.
It is seen that this contact bounce only delays the
output pulse a corresponding time; the energy
content of the output pulse is essentially unaffected.

11

Figure 9 illustrates the effect of lead resistance in the input circuit to the filter of figure 3. A 28-volt step wave was first applied directly to the input of the filter and then to the input through resistive leads having a total resistance equal to 10 percent of the dc input resistance of the filter. The output voltages across a 1-ohm load show that the effect of the resistive input leads on the energy content of the pulse is slight; they simply decrease the peak value of the pulse a small amount and increase its total duration. The net result is about a 5 percent decrease in total energy delivered to the 1-ohm load. In this case the resistive leads comprised a 30-foot length of a twisted pair of No. 22 (7x30) hookup wire and their resistance of 0.89 ohm is judged to be the greatest that one might expect in any practical application. Tests have also been conducted with 30-foot lengths of coax and twinax cables that have a high capacitance per unit length. The capacity of these cables was found to have no effect upon the output voltages; their resistance was the only significant cable parameter.

It should be noted that the curves of the previous figures were obtained by first applying step-wave input voltages to the filter several times so that the magnetic core material was biased in the same direction as it was driven in obtaining these curves. Thus, as far as the residual induction of the core material is concerned, the results presented in each case represent the minimum energy that will be delivered by the filter. If, instead, the filter is first biased in the backward direction and then has a 28-volt step wave applied to its input, somewhat more energy is delivered to the load. This is illustrated in figure 10 for a 28-volt step wave input and a 1-ohm resistive load. The output voltage across the 1-ohm load that lasts the longer time corresponds to the condition of backward bias and it delivers about 5 percent more energy than the shorter pulse. The shorter pulse corresponds to the condition of forward bias and is identical to the pulse shown in figure 4.

b. RF Protection

Since power attenuation specifies the fraction of total input power that reaches a load, it is the most meaningful description of a filter's protective ability. Unlike insertion loss measurements which give different results for different generators, input line lengths, and configurations, power attenuation
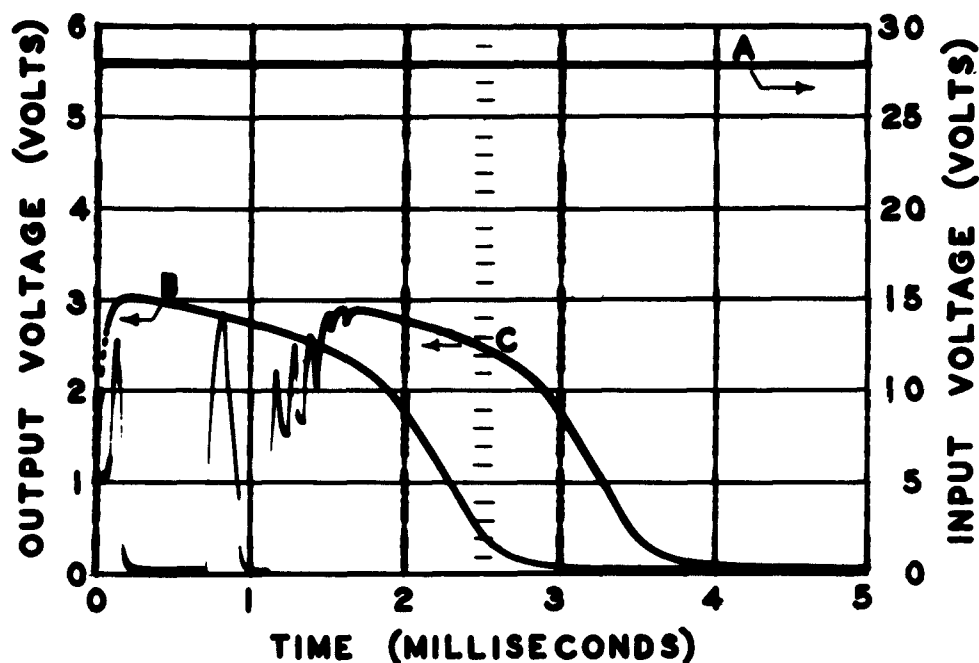
12
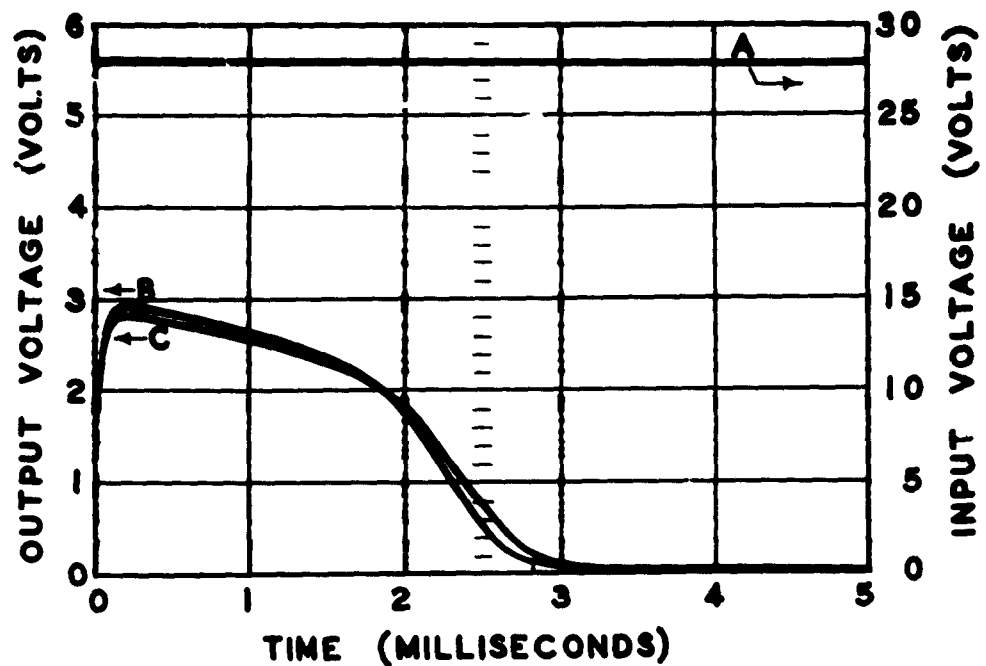
Figure 9. A graph showing the effect of lead resistance in the input circuit of the filter of figure 3.

Curve B shows the output voltage across a 1-ohm load for the filter of figure 3 when a 28-volt step wave (curve A) is applied directly to its input. Curve C shows the corresponding output voltage when the input leads to the filter have a resistance equal to 10 percent of the dc input resistance of the filter. This lead resistance decreases the total energy delivered to the 1-ohm load by about 5 percent.
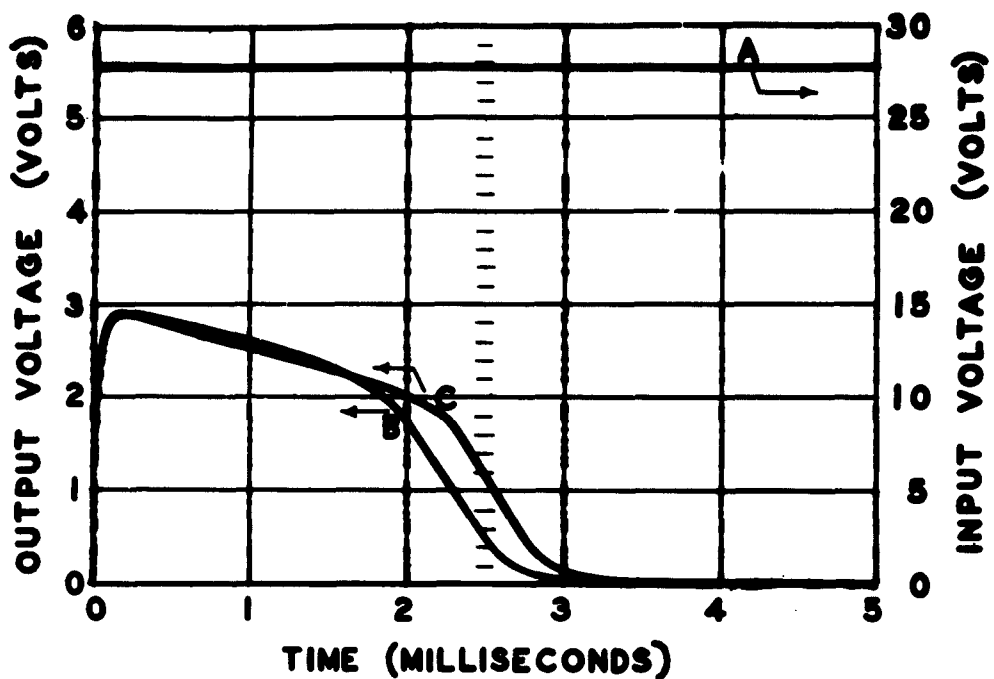
Figure 10. A graph showing the effect of backward bias.

For reference, curve B shows one of a succession of output voltage pulses across a 1-ohm load when a succession of 28-volt step wave inputs (curve A) is applied to the filter of figure 3. Curve C shows the corresponding output obtained when the core material initially has its maximum residual induction in the backward direction. The voltage pulse of curve C delivers to the 1-ohm load about 5 percent more energy than does that of curve B.

14

is a unique characteristic of the filter itself and is independent of mismatches or resonances on the input leads to the filter. Thus, if the power attenuation of a filter is 30 db, for example, one can be certain under all conditions that exactly 1/1,000 of the total power delivered to the filter will reach the load.

Power attenuation measurements were conducted on the filter of figure 3 with a 0.65-ohm load up to a frequency of 10 kmc. No resonances were observed and the number of measurements was sufficient to ensure that none went unobserved. For these measurements, the output power above 2 mc was less than the minimum detectable level of about 0.02 microwatt. With the input powers available, this indicated that the power attenuation is greater than 68 db from 2 mc to 100 mc and greater than 80 db from 100 mc to 10 kmc. However, it is most likely that the power attenuation is much greater than this because it is 59 db at 1 mc increasing at the rate of about 30 db per decade. Thus, at 10 mc one would expect the power attenuation to be at least 59+30=89 db.

The power attenuation of the filter in figure 3 with various loads is shown by the curves of figure 11. By interpolation, the power attenuation at 200 kc for loads of 0.7, 1.0, and 1.3 ohms is, respectively, 33, 32 and 31 db. (The bridge wire resistance of a MK-1 squib varies from 0.7 to 1.3 ohms.) Since a MK-1 squib requires a minimum power of about 0.1 watt for ignition, this means that an input power in excess of 100 watts would have to be delivered to the filter at 200 kc to ignite the squib.

The input power for these power-attenuation measurements was determined by calorimetric methods. For each measurement, power was delivered to the filter for 30 seconds and the temperature rise it produced was measured by a system consisting of a thermocouple attached to the filter case, a dc amplifier, and a recorder. Input powers as low as 0.1 watt were measurable to within about 5 percent accuracy with this system. Calibration was achieved by delivering known amounts of dc power to the filter.

The output power was determined by using an insulated heater type of vacuum thermocouple as the load and measuring its output with an amplifier-recorder system. Vacuum thermocouples having different heater resistances
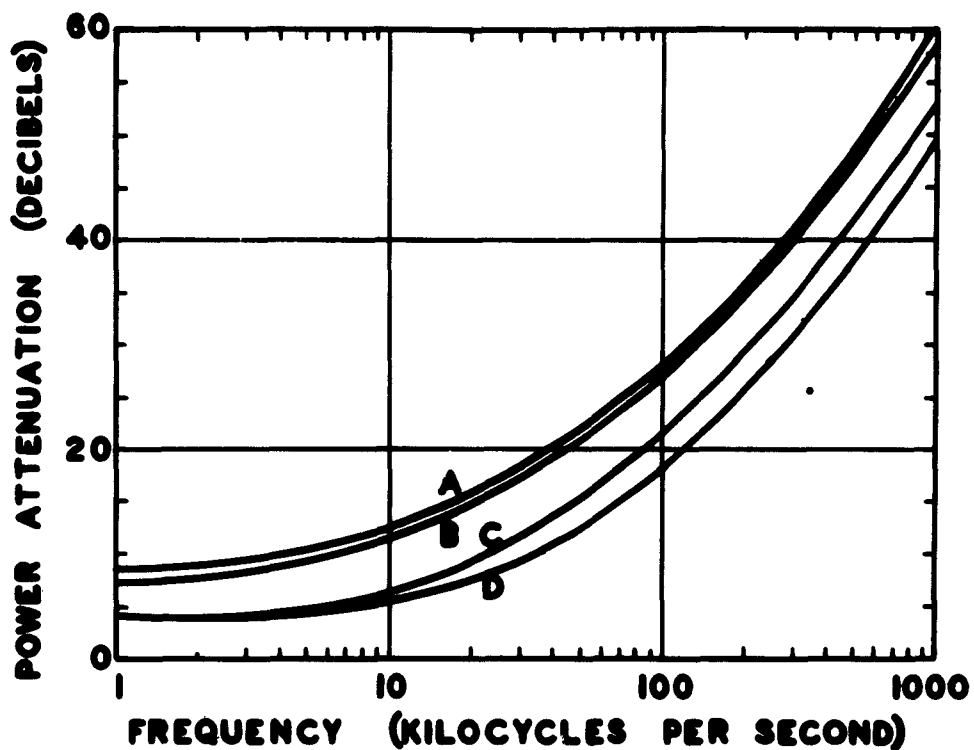
15

Figure 11. A graph of power attenuation vs. frequency for
various resistive loads.

The curves A, B, C, D show power attenuation
vs. frequency for the filter of figure 3 when
terminated by loads of 0.40, 0.65, 1.98, and
4.67 ohms, respectively. By interpolation,
the power attenuation for a 1.0 ohm load is 32
db at 200 kc.

16

were used for the various loads and each was calibrated with dc power. Depending upon the particular vacuum thermocouple that was used, the minimum detectable output power ranged from about 0.005 to 0.03 microwatt.

c. Effects of nearby 60-cps and 400-cps currents.

The effects of large 60 cps and 400 cps currents flowing near the filter of figure 3 were also investigated. With one turn of a single lead carrying 20 amperes of either 60 cps or 400 cps current wound directly on the filter itself, the voltage across the 1-ohm load resistor of the filter was less than 2.5 millivolts. With the input leads to the filter comprising 30 feet of unshielded twisted pair, and with a single lead carrying 10 amperes of either 60 cps or 400 cps current taped to the twisted pair that were either "open" or shorted together, the voltage across the 1-ohm load resistor of the filter was less than the 40-microvolt sensitivity of the measurement. While these tests are quite severe compared to what might actually occur in practice, they do serve to indicate that there should be little concern about the existence of nearby large currents.

3. GENERAL DISCUSSION.

Filters employing the complete shielding concept can be designed to a wide variety of specifications. Some units have been designed to deliver as much as 125 millijoules (1,250,000 ergs) to a load when a 28-volt step wave is applied and to have a power attenuation greater than 30 db at all frequencies above 20 kc; some units have been designed for use with EED's having dual bridge wires that provide reliability through redundancy; other units have been designed for ac firing systems; still other units have been designed for 300-volt dc low current drain firing systems. In this last instance, the current drawn from the 300-volt supply is no more than 170 milliamperes, since the dc input resistance of the filter is 1,750 ohms; and yet the filter delivers a peak current in excess of 2.3 amperes to a 1-ohm load. More particularly, 1 millisecond after the 300-volt step wave is applied, the current drawn from the supply is only 105 milliamperes and the current in the 1-ohm load is 2.35 amperes. This 22-fold step-up in current illustrates that these filters can

17

also be used to advantage in matching high-impedance power supplies, both ac and dc, to low-impedance EED's.

Figure 12 shows a filter that is being developed for use with Eagle-Picher automatically activated batteries. This filter has two separate outputs that are connected to two independent bridge wires of a gas generator which is joined to the left end of the filter. The dc input resistance of this filter is 7 ohms to ensure that the current drawn from a 28-volt supply does not exceed 4 amperes.

The weight and volume of these filters are essentially determined by considerations relating to the intentional firing of an EED; the continuous shield that provides the RF protection needs, by itself, to contribute very little to weight or volume. Thus, when the input voltage to a filter and its load resistance are specified, the two most important factors in determining the weight and volume of the filter are the energy that it must deliver to the load and the minimum input resistance that it may have. Naturally enough, the smaller each of these is, the smaller the filter can be. Other factors that may affect the size of a filter are the time in which the specified energy must be delivered to the load and the amount of attenuation that the filter must provide at the lowest frequency of concern.

To illustrate the lightness and weight-saving potentialities of these filters, it is instructive to express their weight in terms of well known components used in EED firing systems. Feet of 1/8 inch ID shielding braid is an appropriate weight term because braid is often used over twisted pair input leads but it is unnecessary with these filters which additionally provide far greater RF protection. In terms of this new "unit of weight," the filter of figure 3 "weighs" only 8 feet of standard 1/8-inch ID shielding braid. This shows how little it takes to actually save weight with these filters. Comparison of the degree of RF protection obtained in terms of the weight of components required by other systems should be equally favorable.

It should be noted that these filters do not automatically open-circuit themselves as squibs usually do when they fire. Since some systems place critical reliance on the squibs opening the circuit to the firing supply, the use

18

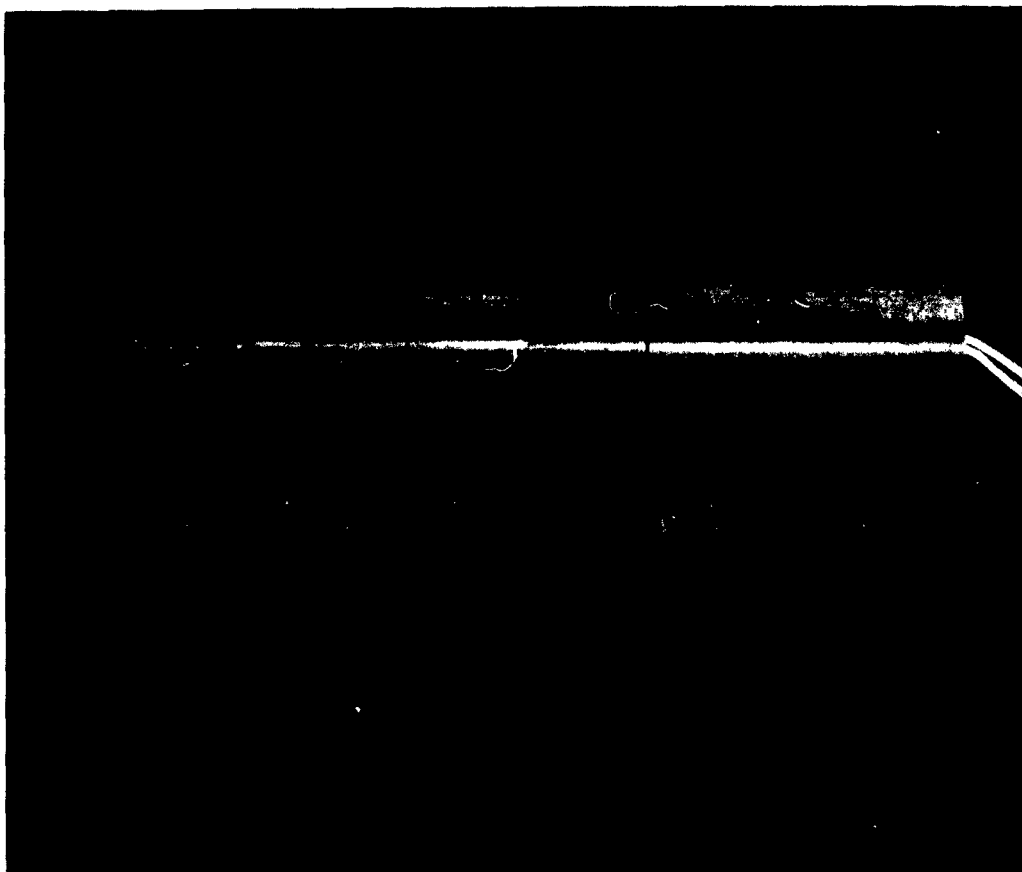Figure 12. A photograph showing a filter designed for use with Eagle-Picher automatically activated batteries.

This filter has two separate outputs that are connected to the two independent bridge wires of the gas generator which is joined to the left-hand end of the filter. The dc input resistance of this filter is 7 ohms to ensure that the current drawn from a 28-volt supply does not exceed 4 amperes.

19

of these filters in those systems would require installation of a circuit-opening device.

Many systems, however, would not require the installation of a circuit-opening device. In some systems, circuit opening is already provided, either by switches or as a consequence of firing the EED (e.g., cable disconnect in rocket firing). In other systems, such as most pulse-firing or capacitor-discharge firing systems, circuit opening is immaterial. It is also immaterial with single-function firing supplies where the fate of the supply after firing the EED is of no concern (e.g., warhead detonation).

In addition to their relatively light weight, these filters have many other advantages. They are simple, passive, and rugged. They contain no semiconducting materials and they are operable over a temperature range at least as great as that of the EED's they are to be used with. They can be designed for ac, dc, pulse, or capacitor-discharge firing systems. They can be used advantageously to match a high-impedance firing supply to a low-impedance EED. They protect an EED from dc ground currents which, even though they may not fire the EED, can degrade an EED so that it may never be operable. The outstanding advantage of these filters, however, is that they provide an EED with unquestioned immunity to all RF frequencies.

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1. Electromagnetic
   radiation
2. Explosive -- elec-
   tric transducers --
   shielding
3. Radio-frequency
   filters
4. Shielding
5. Squibs -- shielding

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2. Explosive -- elec-
   tric transducers --
   shielding
3. Radio-frequency
   filters
4. Shielding
5. Squibs -- shielding

I. AFSC Project 5791,
   Task 579111
II. Contract AF 29(601)-
    5358
III. Bjorksten Research
     Labs., Inc., Madison,
     Wis
IV. Dale G. Holinbeck
V. In ASTIA collection

Air Force Weapons Laboratory, Kirtland AF Base,
New Mexico
Rpt. No. RTD TDR 63-3005. AN INDUCTIVELY COUPLED
FILTER PROVIDING COMPLETE RF SHIELDING OF AN
ELECTROEXPLOSIVE DEVICE. 28 p, incl illus, May
1963.
                    Unclassified report

A filter is described which will protect an elec-
troexplosive device from RF hazards by completely
enclosing the electroexplosive device within a
metallic shield that has no openings or leads
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Experimental power attenuation vs. frequency
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